Investigation of Soybean Oil as a Diesel Fuel Extender: Endurance Tests

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ABSTRACT

Engine performance and crankcase lubricant viscosity were followed with 1:2 and 1:1 fuel mixtures of degummed soybean oil in No. 2 diesel fuel in tests with a John Deere 6-cylinder, 404 cubic in. displacement, direct-injection, turbocharged engine for a total of 600 running hours. A crankcase oil contamination problem resulting in an unacceptable thickening and a potential for gelling did exist with a 50/50 blend or a greater concentration of soybean oil, but it did not occur with the 1:2 blend. The data accumulated during the initial 600 hr running time indicates that a fuel blend of one-third degummed soybean oil and two-thirds No. 2 diesel (1:2 blend) may be a suitable fuel for agricultural equipment during periods of diesel fuel shortages or allocations. Additional data are being accumulated and will be analyzed in the future.

INTRODUCTION

The Johnson Environmental and Energy Center has been interested in alternative fuels for several years. From August 1980 to February 1982, the center was under contract with Gold Kist Inc., a large agribusiness cooperative, to study the feasibility of using plant oil, particularly soybean oil, as a diesel fuel substitute (1, 2). Gold Kist Inc. was the recipient of a Department of Energy grant for this study.

There have been numerous grass roots demonstrations of soybean oil, straight or blended, as a fuel for diesel engines, but the resulting reports were either incomplete or conflicting (3-5). These tests have been performed for reasons ranging from protection against warranty claims to fundamental understanding of the use of plant oils as fuel extenders, emergency fuels, or fuels of the future in some petroleum-poor nations (6).

Engine manufacturers and other investigators have noted two problems as the results of using plant oils, including soybean oil, as a fuel or as a fuel blend. First, a thickening of crankcase oil has occurred which is attributed to the contamination of petroleum-based crankcase oil with unburned plant oil. Second, a buildup of carbon on and in the fuel injector nozzles was observed. The majority of the tests where these problems occurred were conducted using either a blend of 50% plant oils and 50% diesel fuel or using 100% plant oils.

The observed thickening of the crankcase oil from previous demonstrations and/or tests appeared to occur on an exponential curve, i.e., it took a long time to start, after which it happened very rapidly. Previous reports do not specifically define the chemistry of the oil thickening, but it appeared to be a function of the quantity of unburned plant oil in the combustion cycle which was "wiped down" into the crankcase, thereby contaminating the petroleum-based crankcase oil. If this were true, then a fuel blend of less than 50% plant oil would result in less unburned plant oil contaminating the crankcase oil. It appeared possible that the undesirable oil thickening could be delayed beyond the normal crankcase oil change interval.

EXPERIMENTAL PROCEDURES

Fuel Characteristics

Prior to undertaking engine tests using soybean oil as a portion of the fuel, the energy content of crude, degummed, once refined and salad grade soybean oil was studied. The energy content, 128,600 Btu/gal, remained reasonable constant for all of the grades of soybean oil. Degumming appeared to be necessary to minimize the potential for fouling the diesel engine injector pump and the filters. Further refining or processing, beyond degumming, did not appear to offer any benefits if the soybean oil was to be used as a motor fuel.

Flash points for the various vegetable oil samples and blends were determined according to ASTM Test Method No. D-93 (Table I).

Comparative viscosity measurements, using a jacketed pipette (Fig. 1) of degummed soybean oil, No. 2 diesel fuel, a blend of one-third degummed soybean oil and two-thirds No. 2 diesel fuel (1:2 blend) and a blend of one-half degummed soybean oil and one-half No. 2 diesel fuel (1:1 blend) are shown in Table II. Results reported are the flow times in seconds required to deliver a fixed volume from a jacketed pipette under the standardized test conditions.

Test Engine and Test Procedures

A John Deere 6-cylinder, 404 cubic in. displacement, direct-injection, turbocharged engine, Model No. 6404TR was used.

After 100 hr of operation on standard (No. 2) diesel fuel, the John Deere diesel engine was tested for operation on both standard diesel fuel and a 1:2 blend of No. 2 diesel and degummed soybean oil. To make the tests as comparable as possible, the crankcase oil and filter were changed at 100 hr running time just prior to the tests. All tests were run during 1.5 hr on April 14, 1981, which kept tests conditions nearly constant.

Fuel flow data were taken four times during a 10-min period for each type of fuel. The maximum variation between mean and extreme values was ± 0.3%.

The two types of tests made were fuel consumption at continuous rated power (117.3 hp at 2200 rpm), and wide-open throttle (maximum intermittent power at 2200 rpm). The tachometer and fuel flow cylinder had been calibrated prior to the tests. The dynamometer was calibrated with dead weights and appeared to need no correction for torque. Fuel density was measured on the day of the test.

Brake thermal efficiency was calculated using textbook data for volumetric energy content of fuels. This means that the absolute values given are subject to some error. However, the relative values appear to be accurate.

A 200-hr run was conducted using a blend of one-third degummed soybean oil and two-thirds No. 2 diesel fuel. The engine test procedure and fuel consumption test procedure were formally documented and used. A test cycle patterned after an Engine Manufacturers' Association recommendation was used. This cycle was: 30 min at 700-900 rpm and no load, 60 min at 2200 rpm and 280 ft lb, 60 min at 1500 rpm and 280 ft lb, and 30 min at 1750 rpm and 70 ft lb.

Although the recommended crankcase oil change interval is 100 running hr, it was not changed until 200 running hr to permit evaluation of crankcase oil contamination. Viscosity readings were taken as shown in Figure 2. Determination of the content of the oil was carried out according to ASTM Procedure No. D-482. The ash was then dissolved

TABLE I

Flash Point

Oil	Flash point (C)
Soybean oil, degummed, GKD, 1980	247
Soybean salad oil, Marks, MS, 1980	340
Soybean oil, once refined, Marks, MS	279
Diesel oil, January 1981	84

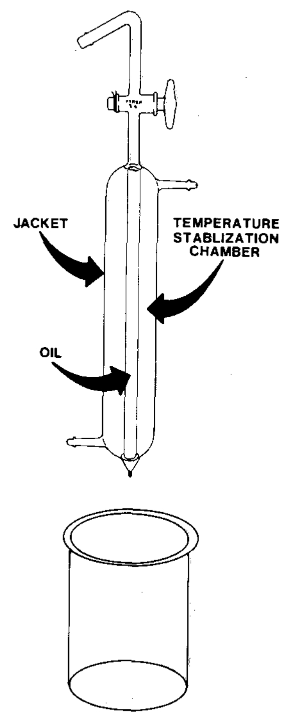

FIG. 1. Jacketed pipette for comparative viscosity measurements.

TABLE II

Comparative Viscosity of Test Fuels[a]

Temperature (C)	Comparative viscosity (sec)			
	Soybean oil	Diesel	1:2 Blend	1:1 Blend
70	34.2	23.5		26.2
60	37.6	23.5		26.9
50	42.2	23.9		28.25
40	51.7	24.4		29.8
30	66.1	24.8		32.4
20	85.7	25.6	30.7	35.6
10	129.2	26.5		41.3
5	163.3	27.6	35.7	46.8
0	216.1	28.1	39.4	53.3
-5	282.1	29.1	43.3	60.5
-10	833.0[b]	30.7	49.0	72.6
-15		32.4	58.3	102.1

[a]Measurements using a jacketed pipette.
[b]Cloud point.

in 1.0% nitric acid, and metals were determined by atomic absorption spectrophotometry (Table III).

In an effort either to reveal some errors in our test procedure or to confirm the crankcase contamination problems found by other investigators, a 200-hr run was conducted without changing crankcase oil using a blend of one-half degummed soybean oil and one-half No. 2 diesel (1:1 blend). Comparative viscosity readings were taken as shown in Figure 3.

Following a 400-hr endurance run using the 1:2 fuel blend, the engine was partially disassembled for inspection. The total engine time was 930 hr as follows: 100 hr calibration with No. 2 diesel, 200 hr crankcase oil contamination investigation with 1:2 blend, 200 hr crankcase oil contamination investigation with 1:1 blend, 30 hr with No. 2 diesel and Dee Zol, and 400 hr endurance run with 1:2 blend. The results of the 400-hr endurance run are shown in Table IV.

Figure 4 depicts the horsepower and thermal efficiency data recorded during the 900 hr.

Laboratory Production of Thickened Crankcase Oil

Mixtures were prepared of varying amounts of Texaco Super-3 URSA Motor Oil SAE 30HD and degummed soybean oil from the Decatur Gold Kist plant. Various amounts of water were added, as shown in Table V, because it was suspected that water condensed in the crankcase might be significant in the hardening reaction. The solutions were held at 85-95 C and agitated by aeration for 240 hr (10 days). No significant hardening was noticed without added metals. When catalytic amounts of cobalt and manganese compounds were added, all the mixtures containing 10% or more of soybean oil became dark colored and highly viscous in 94 hr. Stirring and aeration were discontinued at that point, and in the next 24 hr they changed to semisolid gums.

RESULTS AND DISCUSSION

Engine Tests

A 1:2 blend of degummed soybean oil and No. 2 diesel fuel was selected for the test based on market considerations and the need to minimize the viscosity of the soybean oil. It does not appear likely that sufficient undiluted soybean oil would be available to provide the needs of a large percentage of the diesel-powered agricultural equipment and certainly not enough to supply any reasonable portion of the over-the-road equipment. A blend of one-third degummed soybean oil and two-thirds No. 2 diesel potentially would be sufficient to supply the agricultural equipment and would, in event of shortages or allocations, increase the quantity of agricultural fuel available by 50%. Also, this blend would minimize the effect of any small price differential between 100% No. 2 diesel fuel and degummed soybean oil.

During the first 200-hr run the maximum corrected horsepower dropped from 133 at the beginning (2 hr) to 121 at the end (201 hr). The test or continuous horsepower remained at 117.3 throughout the 200-hr run. Corrected thermal efficiency varied from 28.9% at the beginning to 28.6% at the end (see Table VI).

Based on the viscosity of the crankcase oil, the horsepower and thermal efficiency figures, it was concluded that the blend of one-third degummed soybean oil and two-thirds No. 2 diesel was an acceptable fuel. The crankcase oil did not appear to have been contaminated to a significant degree and thickening or gelling did not occur.

At the conclusion of the 200-hr run with the one-third/two-thirds blend of degummed soybean oil and No. 2 diesel (1:2 blend), performance data were recorded on the one-half/one-half blend (1:1 blend) (Table VII).

During the 200-hr run using the 50/50 blend, the corrected maximum horsepower dropped from 131 to 120.5 at 129 running hours. After cleaning the injectors it recovered to 122.7 horsepower but later dropped to 113.3. It

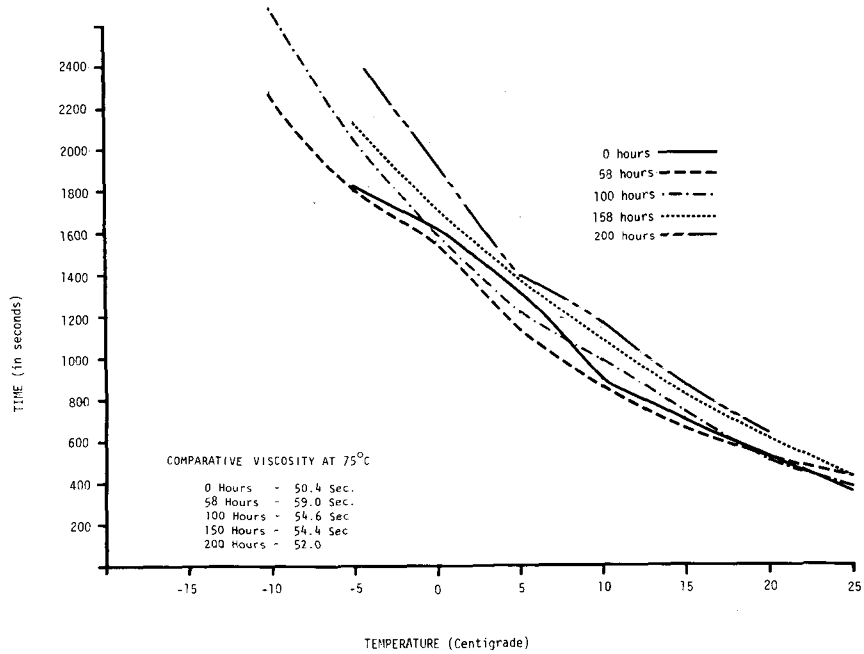

FIG. 2. Comparative viscosity measurements for the crankcase oil during the 200-hr run with the 1:2 (soybean oil/diesel oil) run.

TABLE III

Ash and Metals in Crankcase Oil

Running time (hr)	Fuel	Ash (g/10mL)	Metals (ppm)			
			Mn	Co	Ni	Pb
0	–	0.0730	5.75	0.44	0.30	0.14
100	No. 2 diesel	0.1311	8.47	0.68	0.46	0.17
100	33:66	0.0915	8.74	0.49	0.46	0.17

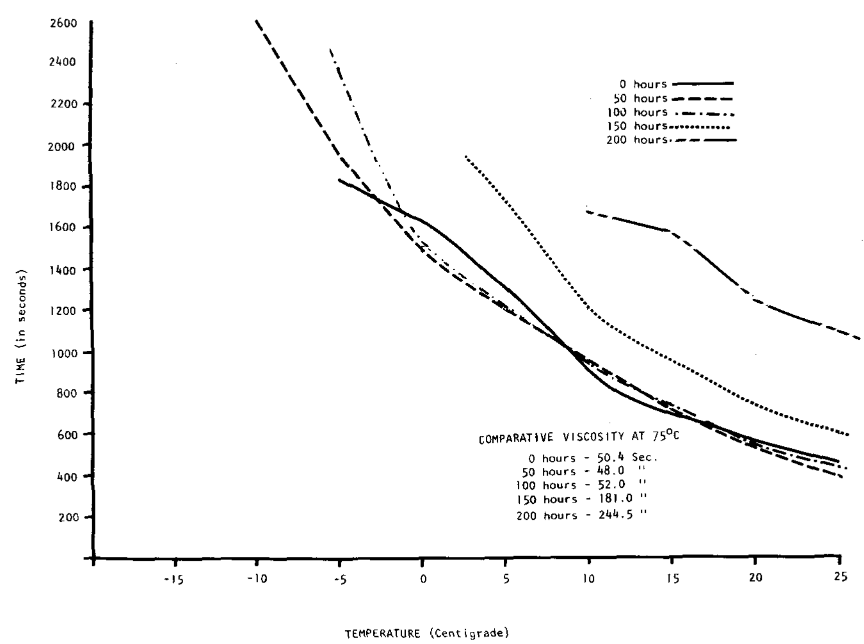

FIG. 3. Comparative viscosity measurements for the crankcase oil during the 200-hr run with the 1:1 (soybean oil/diesel oil) run.

TABLE IV

Engine Performance from EMA Cycle Tests — 1:2 Fuel Blend

Running hours	Corrected thermal efficiency	Corrected maximum horsepower
1	29.43	123.6
129	28.91	106.22
139	28.03	108.07
194	28.26	108.4
272	29.10	106.64
283	29.52	110.14
306	28.93	105.8
328	27.8	105.2
330	28.82	105.3
399	27.04	106.6
400	27.25	107.45

TABLE V

Crankcase Oil Hardening Experiments (without added metals)

Crankcase oil (%)	Soybean oil (%)	Water added (mL/100 mL oil mixture)			
		1	2	5	10
99	1	E(b)	E(b)	E(b)	E
98	2	E(b)	E(b)	E(b)	E(a)
95	5	E(b)	E(b)	E(b)	E(c)
90	10	E(b)	E(b)	E(b)	E(c)
80	20	E(b)	E(b)	E(b)	E(c)
50	50	E(b)	E(b)	E(b)	E(c)
100	0	E(b)	E(b)	E(b)	E(c)

[a]Emulsion "broke" after 20 min.

[b]Emulsion separated from oil mixture, after two weeks.

[c]Emulsion segregates into 3 distinguishable layers: oil, emulsion and water, or a lighter colored emulsion.

The oil mixtures used for this experiment were blended from the following material: soybean oil: Goldkist-Decatur, Alabama, degummed, 9-25-80; crankcase oil: Texaco Super-3 URSA Motor Oil SAF 30 HD.

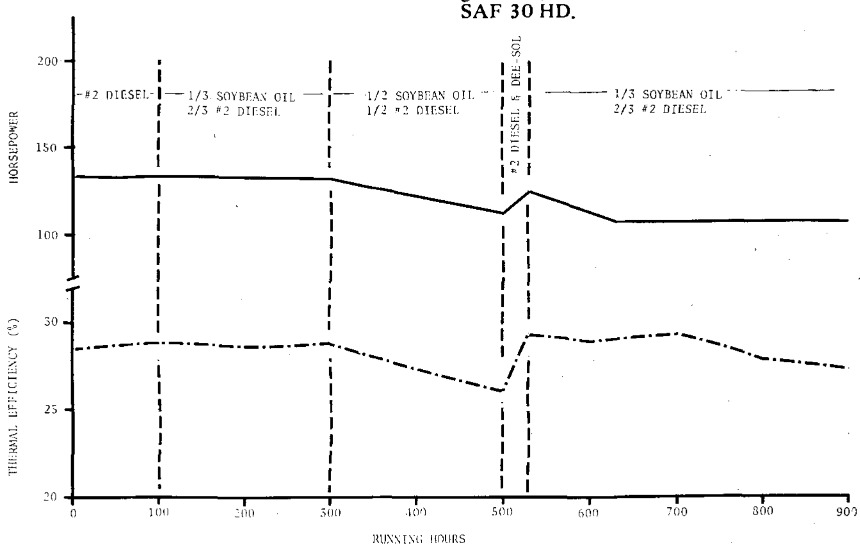

FIG. 4. Horsepower and thermal efficiency during the course of 900 hr of operation.

TABLE VI

Engine Performance from EMA Cycle Tests

	2D Fuel (2 hr)	2:1 Fuel (2 hr)	2:1 Fuel (105 hr)	2:1 Fuel (152 hr)	2:1 Fuel (201 hr)
Corrected brake thermal efficiency (%)	28.5	28.9	28.9	28.3	28.6
Corrected maximum horsepower	133	133	131	132	131

TABLE VII

Comparative Brake Thermal Efficiency

	2D Diesel[a] fuel	2:1 Blend 2D/soy[a]	1:1 Blend 2D/soy[a]
Density at 80 F (lb/gal)	7.06	7.14	7.30
Heating value (Btu/gal)	140,000	136,761	135,142
Heating value (Btu/lb)	19,830	19,154	18,513
Maximum intermittent horsepower	136	136	
Normal continuous horsepower	117.3	117.3	117.3
Specific fuel consumption (gal/bhp hr)	0.06289	0.06292	0.06567
Specific fuel consumption (lb/bhp hr)	0.4398	0.4493	0.4794
Brake thermal efficiency (%) (uncorrected)	29.18	29.57	28.67

Note: All these tests were run with fresh crankcase oil.

[a]No. 2 diesel.

appears probably that carbon deposits on the injectors from the 50/50 fuel blend and thickening of the crankcase oil contributed to this decrease in power (see Table VIII).

The results of the two 200-hr runs investigating crankcase contamination indicated that a 1:2 blend of degummed soybean oil and No. 2 diesel posed no threat to loss of lubrication. An endurance test of 400 hr running time was then performed using the 1:2 fuel blend. A 30-hr run with 100% No. 2 diesel and an additive, Dee Zol, was performed before beginning the endurance test in an attempt to remove some of the excess carbon in the engine as a result of the 50/50 fuel blend test.

Engine brake thermal efficiency tests were carried out at the end of each of the first two 200-hr cycles. These data (Table VII) indicate that the blended fuel burns almost exactly as well as No. 2 diesel fuel in this engine. This conclusion is somewhat confirmed by the very clear exhaust observed at all loads with blended fuel. Also, there is no apparent difference in startability between the fuels.

The results of the 400-hr endurance run are shown in Table IV. The drop of horsepower from 123.6 to 106.22 at 129 hr was determined upon disassembly of the engine for inspection to be the result of no. 1 cylinder injector being "frozen" shut. Under this condition cylinder no. 1 did not contribute any power. It is important to note that from 129 hr to 400 hr there was no significant deterioration in engine performance.

Upon removal of the head it was found that cylinder no. no. 1 injector was stuck in the closed position, and cylinder no. 6 sleeve and piston were scored. There was a layer of carbon ca. 1 mm thick on the top of five pistons (Table IX). No. 1 had a layer 2.61 mm thick. There was a layer of carbon on the valve stems (Table X). No. 1 intake valve stem had the least and the exhaust had the greatest buildup. Cylinders 2-5 were about the same.

With the possible exception of the carbon deposits on pistons and valves, none of the deficiencies found could be positively attributed to the use of soybean oil in the fuel. It appears that the cylinder no. 1 injector stuck in the closed position at some time during the first 129 hr of the 400-hr endurance run. Since this cylinder was no longer contributing to the power output, it could conceivably account for the power drop noted after the 123.6 horsepower reading at the beginning of the endurance run.

The cylinder no. 6 sleeve and piston were replaced along with the crankshaft bearings and the engine was reassembled.

A planned additional 600-hr endurance test has been initiated. If successful, this will bring the total up to 1200 hr using the 1:2 blend of degummed soybean oil and No. 2 diesel. After 26 hr, the turbocharger developed an oil leak and had to be replaced.

Figure 4 shows the raw performance data recorded after reassembly. These data have not yet been fully analyzed. However, the engine easily accommodates 280 ft lb torque at 2200 rpm or 117.3 continuous horsepower.

Lubricating Oil Tests

Comparative viscosities for the lubricating oil during the first 200-hr run with the 1:2 blend are shown in Figure 2, and the analyses for ash and metal content are given in Table III. The measurements show significant changes after 100 hr of operation. Ash, manganese, cobalt, nickel and lead all increased. Of the metals, manganese showed the greatest increase. Since manganese is known to catalyze hardening of plant oils, both in the paint and varnish industry and in our laboratory experiments, its increase is considered potentially significant. Presumably it enters the oil as a result of engine wear, since manganese is a component of steel.

Comparative viscosities for the lubricating oil during the second 200-hr run with the 1:1 blend are given in Figure 3. Considerably greater thickening of the lubricating oil occurred compared to the 1:2 blend. It is interesting to note that the crankcase oil sample taken for the viscosity check after 200 hr did gel shortly after the viscosity data were recorded.

It was concluded that a crankcase oil contamination problem resulting in an unacceptable thickening and a potential for gelling did exist with a 50/50 blend or a greater concentration of soybean oil but it did not occur with the 1:2 blend.

Experiments were performed in the laboratory on production of thickened or gelled crankcase oil from various mixtures of lubricating oil with degummed soybean oil in the presence of water (Table V) and also in the presence of added metals. No significant hardening was noticed without added metals. When catalytic amounts of cobalt and manganese compounds were added, all the mixtures containing 100% or more of soybean oil became dark colored and highly viscous in 94 hr. Stirring and aeration were discontinued at that point, and in the next 24 hr they changed to semisolid gums.

These experiments permit several conclusions. First, the process appears to be independent of the amount of water present. Second, it is very sensitive to catalysis by compounds of manganese and cobalt. Third, a fairly high concentration of soybean oil (10%) was required to produce thickening under the laboratory conditions. In view of the

TABLE VIII

Engine Performance from EMA Cycle Tests

	Corrected brake thermal efficiency (%)	Corrected maximum horsepower
2D Fuel (2 hr)	28.5	133
2:1 Fuel (2 hr)	28.9	133
1:1 Fuel (3 hr)	28.9	131
1:1 Fuel (85 hr)	29.0	126
1:1 Fuel (129 hr)	28.4	120.5
Injectors cleaned		
1:1 Fuel (178 hr)	27.64	122.7
1:1 Fuel (199 hr)	26.13	113.3

TABLE IX

Average Carbon Thickness on Top of Piston

	mm
1	2.61
2	1.05
3	1.06
4	0.95
5	0.95
6	0.94

TABLE X

Carbon Thickness on Valve Stem (Stem = 0.372 in.)

	Intake				Exhaust			
#	Avg	Δ	Max	Δ	Avg	Δ	Max	Δ
1	.384	.012	.422	.050	.533	.162	.613	.241
2	.401	.032	.417	.045	.379	.007	.388	.015
3	.404	.035	.426	.054	.381	.009	.390	.018
4	.420	.048	.425	.053	.384	.012	.388	.016
5	.404	.035	.426	.054	.379	.007	.387	.015
6	.410	.038	.459	.087	.382	.010	.387	.015

different performance in the engine of the new lubricating oil used in the final engine test, the conclusions stated can be applied strictly only to the oil used in the laboratory tests.

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Winter Rape Oil Fuel for Diesel Engines: Recovery and Utilization[1]

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ABSTRACT

Although vegetable oil cannot yet be recommended as a fuel for general use, considerable progress in recovery and use of rapeseed oil (*Brassica napus* L.) for diesel operation has been made. Operation of a small-scale screwpress plant (40 kg/hr) was demonstrated. Maintenance of screw and end rings was a major problem. The plant has operated with a recovery efficiency of 77% and has processed 10,100 kg of seed in 230 hr. High viscosity of the rapeseed oil and its tendency to polymerize within the cylinder were major chemical and physical problems encountered. Attempts to reduce the viscosity of the vegetable oil by preheating the fuel were not successful in sufficiently increasing the temperature of the fuel at the injector to be of value. Short-term engine performance with vegetable oils as a fuel in any proportion show power output and fuel consumption to be equivalent to the diesel-fueled engines. Severe engine damage occurred in a very short time period in tests of maximum power with varying engine rpm. Additional torque tests with all blends need to be conducted. A blend of 70/30 winter rape and No. 1 diesel has been used successfully to power a small single-cylinder diesel engine for 850 hr. No adverse wear, effect on lubricating oil or effect on power output were noted.

INTRODUCTION

Agricultural production in the United States requires 8.3 billion liters of diesel fuel to produce crops from 138 million hectares of cropland. In Idaho, 155 million liters of diesel fuel are required to produce crops from 2.7 million hectares of cropland. Between 55 and 60 liters of diesel fuel are required for each hectare of crop production.

The possibility of using vegetable oils as a direct substitute for diesel fuel is one of several concepts for on-farm production of fuel. Vegetable oils show promise of providing all the liquid fuel needed on a typical farm by diverting 10% or less of the total acreage to fuel production (1-4). The meal remaining from the fuel extraction can be a source of high protein livestock feed replacing the soybean meal currently imported into the Pacific Northwest. Further, the extraction and processing of vegetable oil is a simple low energy process that makes use of equipment not unlike that with which farmers are already familiar.

Winter rape (*Brassica napus*) is adapted for production in the Palouse region of Northern Idaho and Eastern Washington. Current production, however, is less than 3000 ha. Dwarf Essex, the cultivar currently produced, is a nonedible variety produced only for industrial use of the oil. The oil contains ca. 50% erucic acid and the meal contains high levels of glucosinolates which break down in the intestines of livestock to form toxic byproducts (Appelquist and Ohlson, 1972). Bettis (5) provides a detailed description of winter rape.

Even though the total acreage of winter rape is presently small, the adaptability of the crop, yield of oil per acre, and low iodine number make it an attractive source of emergency fuel to guarantee the continued agricultural production of the area in case of a petroleum shortage. The varieties of winter rape presently grown are high in erucic acid, high in glucosinolates, and the oil produced has a viscosity ca. 17 times that of diesel fuel. These factors present problems requiring special consideration if winter rape is to be used economically and reliably as a fuel.

Recent interest has focused attention on winter rape because of its high oil content (45%) and its high potential yield, in excess of 5000 kg/ha, in experimental trials. Current commercial average yields in the Palouse are close to 2000 kg/ha. Agronomic optimization of the crop through breeding and management appear to have great opportunity.

Tests of vegetable oils as diesel fuel replacements have been generally satisfactory in short-term tests but have resulted in undesirable combustion chamber deposits in long-term tests. Evidence suggests that the best means of reducing these deposits may be through use of the more saturated vegetable oils such as high erucic or oleic oils.

This paper discusses the experimental tests in progress at the University of Idaho investigating extraction and use of high erucic acid winter rape for use as a blend with diesel fuel. The program is interdisciplinary, involving plant scientists, chemical and agricultural engineers, animal scientists and agricultural economists seeking solutions to production, extraction and utilization of both oil and meal.

EXPERIMENTAL

The winter rape oil used in these tests was processed with a CeCoCo expeller operated by the University of Idaho. Filtering the sediment was the only additional processing. The oil was evaluated to determine: (a) fatty acid composition, (b) specific gravity, (c) viscosity, (d) heat of combustion, and (e) ash content. The oil was also evaluated in short-term engine tests to determine its effect on engine performance. Three cycles of long-term (830 hr) test have been conducted to evaluate potential effects on engine life.

Fatty acid composition was determined on a Packard-Becker model 419 gas chromatograph with a flame ionization detector. Physical characteristics were evaluated in

[1]Approved as Paper No. 8237 of the Idaho Agricultural Experiment Station.